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PROBLEMS ASSOCIATED WITH THE STUDY OF CORAL REEFS. II

BY PROFESSOR W. M. DAVIS

HARVARD UNIVERSITY

The Theory of Submerged Platforms.—A modification of the theory that explains barrier reefs as veneers upon wave-cut platforms has been lately and briefly proposed. It regards the lagoon floors as platforms that were produced, while the central island stood higher than now, by some planation process or processes other than those concerned in the production of coral reefs, and then explains the reefs as veneers formed on or near the edge of the platform as it is submerged to its present depth. This theory has the merit of accounting for the embayed shorelines of the central island, inasmuch as the valleys which must have been eroded in it during the planation of the platform while the island stood higher, must have been partly drowned when the platform was submerged; but the theory has the demerits of tacitly postulating the absence of reef-building corals while the platform was being produced, and of leaving the processes by which the platform was produced unspecified. It would be easy to account for the platforms by subaerial planation, if the area that they occupy had consisted of weak rocks in comparison to those of the still mountainous central island, but there is not the least evidence that such was the case. Again, it would be easy to account for the platforms by marine abrasion, if corals were absent; but in that case the central island ought to be rimmed around by cliffs, as in the preceding theory. It is unreasonable to assume that corals were absent; for they have long been present in the coral seas, as is shown by the existence of uplifted and dissected reefs, having embayed shorelines and enclosed by barrier reefs such as the present theory seeks to explain. Moreover the form of the embayments on a good number of islands indicates that the depth of their submergence is decidedly greater than the depth of the lagoon upon which they open, as will be further shown when the glacial-control theory is discussed on a later page. The fact that certain barrier reefs are discontinuous and not always on the outer edge of the platform represented by the lagoon floor has been taken in support of this theory and as indicating that the platform has been produced by other agencies than those which produce reefs; but discontinuity of reefs and their displacement from the platform edge can be well explained by other theories alsc, such as the theory of subsidence, if it be assumed that subsidence proceeds at different rates, now faster, now slower. If the fuller statement of the submerged platform theory, yet to be published, gives good ground for the absence of corals while the platforms were in the making, and reasonable explanation of the manner in which the platforms were made, it would have a better prospect of acceptance.

Darwin's Theory of Subsidence.—Let us now consider the theory formerly so popular, the theory of coral reefs which most of us learned at school or college, but which later came to be regarded by many able geologists as "no longer generally applicable." This theory supposes that the oceanic island or continental border on which a fringing reef is established intermittently subsides while the reef slowly grows upward: thus the fringing reef is transformed into a barrier reef around the diminishing central island, while the coral waste washed over the reef and the land waste washed down from the adjoining land surface, together with organic deposits formed in the lagoon itself, nearly fill the lagoon with horizontal strata; and later, when subsidence has gone so far that the central island has disappeared, the upgrowing barrier reef encloses an uninterrupted lagoon and is called an atoll. Here the associated problem takes on a new form. It is now necessary to work out the changes suffered by an island that is slowly submerged while its surface is eroded and a reef grows up around it. As before we begin in sector *H*, Fig. 13, with a large volcanic island, built up by frequent eruptions from the ocean bottom to some thousands of feet above the ocean surface. In due time a narrow fringing reef is established around its shores, interrupted at stream mouths where much detritus is washed down from the sharp-cut young valleys. Subsidence may have been going on slowly while eruptive upbuilding was going on more rapidly; now eruption has ceased, but subsidence is assumed to continue. What will be its effects? The effects of elaborate dissection

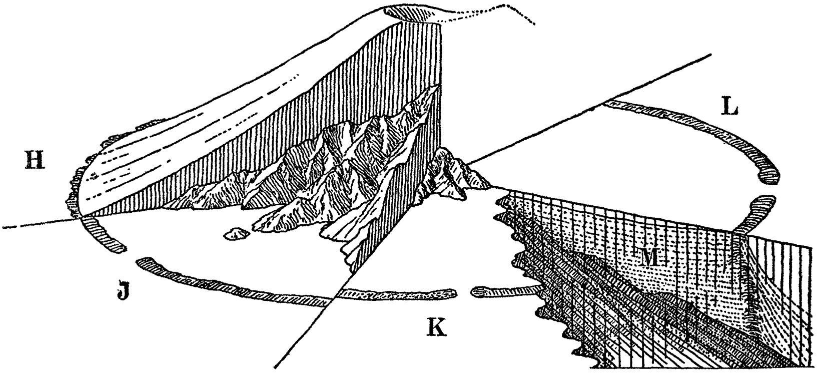

FIG. 13. DIAGRAM OF SUCCESSIVE SECTORS OF REEF FORMATION, as deduced from Darwin's theory of upgrowing reefs on subsiding islands.

and moderate subsidence are shown in sector *J*; the effects of continued dissection and greater subsidence in sector *K*: and of complete submergence in sector *L*. This may be illustrated in another manner: During the progressive changes caused by erosion and subsidence, the simple initial shoreline of the central island consequent on eruption, shown in the background block of Fig. 14, must be changed to an indented or embayed shoreline consequent on the partial submergence of a dissected cone, as shown in the middle section of the figure. Eventually the island sinks out of sight and the atoll reef grows up, enclosing the uninterrupted lagoon, as in the foreground of Fig. 14.

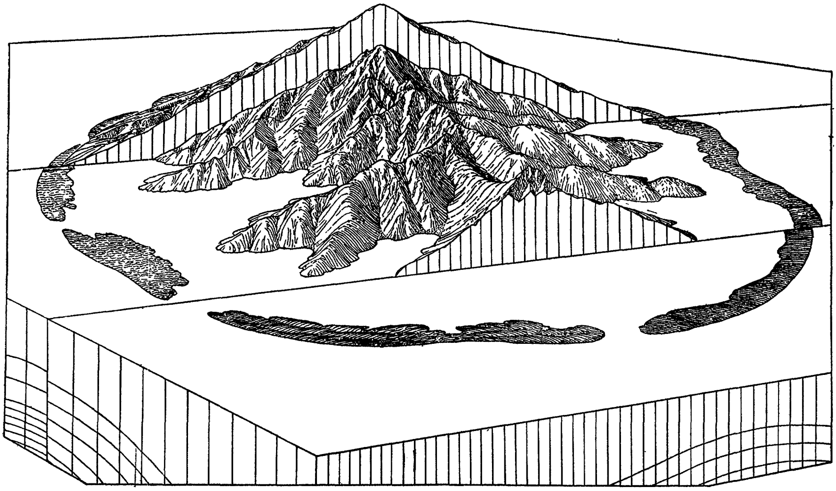

FIG. 14. BLOCK DIAGRAM OF A SUBSIDING VOLCANIC ISLAND IN AN OCEAN OF CONSTANT LEVEL. Background block, a high-standing island with a simple shore line bordered by a fringing reef; middle block, a partly submerged island with an embayed shore line and a barrier reef enclosing a lagoon; foreground block, an atoll reef around an uninterrupted lagoon over a vanished island.

The proportion of the several ingredients in the lagoon deposits will vary according to the size of the reef, the strength of the waves, the size of the island, and so on. The horizontal lagoon layers must rest unconformably on the eroded flanks of the subsiding volcano, as is shown in section *M* on the side of sector *L*, Fig. 13. Outside of the reef there should be a long, sloping talus, largely composed of coral fragments, except that opposite each pass or break in the reef, where the great volume of sea water that surges in over the reef-flat must find its escape, there should be a significant outwash of fine volcanic waste so long as the lagoon is of moderate width; for the lost volume of the initial volcano can not be represented only by the near-shore intermixture of volcanic detritus with the calcareous lagoon beds. The lower ends of the slanting layers of exterior talus thus formed must lie on the submarine constructional slope of the volcanic cone.

Two of these consequences deserve more emphasis. First, it must be understood that production of an indented shoreline, as in Fig. 15, by the subsidence of a dissected island is not a vague speculation; it is a geometrical necessity of the same order as that which defines the pattern of the conic sections; for the intersection of a fluted cone by the level surface of the sea must be an indented line. Second, if the subsidence is accelerated, the reefs may be incompletely built up to the surface, and appear only in narrow and discontinuous patches; or, if subsidence be over-rapid, the reef-building corals may be drowned by being submerged to too great a depth; if the subsidence is then retarded, a new fringing reef will be established on the submerged flanks of the island and will in time develop into a new barrier reef of smaller radius than before; in the early stage of the second reef the amount of subsidence indicated by the breadth of its lagoon will be much less than that indicated by the size of the embayments. But if it is an atoll that is thus drowned, it can not grow up until it is again uplifted nearer the surface or until it is built up to less depth by organisms other than reef-building corals. On the other hand, if subsidence ceases for a sufficient time, a barrier reef will widen by outward growth and inward over-wash, the deltas will be built forward and the lagoon will fill up; thus a broad, mature reef plain will, if the still-stand pause lasts long enough, more or less completely replace the narrow young reef and the lagoon. A brief and small elevation may occur at any stage, uplifting the reef a few feet out of water, when it will be attacked and dissected

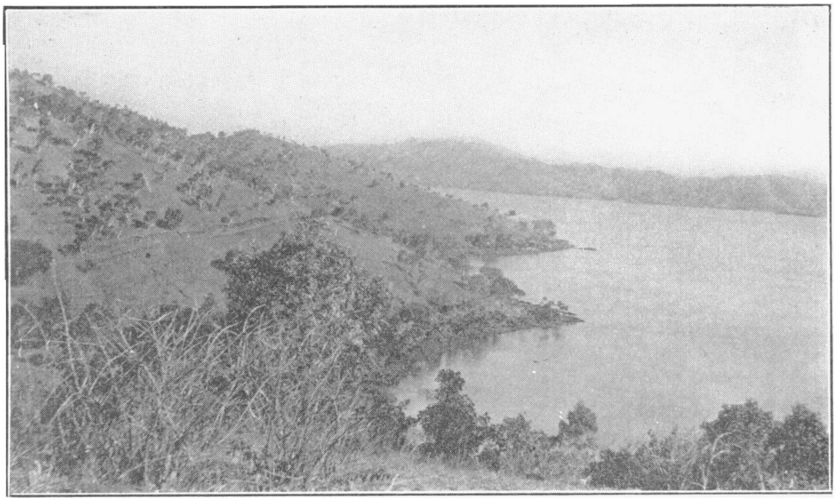

FIG. 15. THE EMBAYED SHORE LINE AT THE NORTHWEST END OF THE PARTLY SUBMERGED ISLAND OF NEW CALEDONIA; the water is part of the large lagoon enclosed by an extensive barrier reef. The farther shore line should be level.

by weather and waves, or submerged if subsidence sets in again. The reason that these consequences are so varied is evidently that subsidence is a much more variable process than standing still.

Success of Darwin's Theory.—Now how did this old theory fare? It gained immediate and universal acceptance. Was this because its author's experience was such as greatly to commend it? By no means; for Darwin was then a young naturalist, just returned from his first and only voyage of exploration. Did he consider other theories also? Yes, he did that most fairly and candidly; the theory of outgrowing reefs around still-standing islands, the theory of veneering reefs on wave-cut platforms, and several other theories were carefully examined, and critical reasons were stated for their rejection. Did the young naturalist deduce all the consequences of his theory, somewhat as above stated? No, not all; he stated several of them clearly enough, but he unfortunately made the serious error of overlooking one of the most essential consequences, namely the occurrence of embayed shorelines around the subsided central islands of barrier reefs; and thus failed to secure for this theory the confirmation that might have come from its success in explaining certain things that it was not invented to explain, as well as all the things that it was invented to explain. Why, then, was his theory received with so great favor? Evidently because those who accepted it were not in the habit of demanding that a successful theory should do something more than explain the things that it was invented to explain, and because they were satisfied on finding that it provided a simple, easily conceived scheme for correlating and explaining the numerous and varied facts that it was made to explain. Was that not enough to establish it? It seems to have been enough, as long as the theory had no serious competitors; for it was not only universally accepted, but as late as 1882 was referred to by an eminent critic as "a theory which for simplicity and grandeur strikes every reader with astonishment. . . . No more admirable example of scientific method was ever given to the world." Darwin's exposition of his theory was certainly admirable, but it is going too far to say that a theory, from which the essential element of independent confirmation was lacking, is as admirable an example of scientific method as the world has seen.

Unwarranted Loss of Faith in Darwin's Theory.—Naturally enough, when another possible theory was put forward, a critic, who had no independent and crucial test in mind by which his belief in an earlier theory was compelled, lost his confidence in it, even though the later one had only the same insufficient recommendation of explaining what it was made to explain; for it was the same critic who, only a year after commending Darwin's theory of subsidence in the glowing terms just quoted, abandoned it and became the avowed champion of the theory of outgrowing reefs on still-standing islands. He may even then have felt the keen regret expressed twenty years later "that this brilliant generalization of the great naturalist [Darwin] has been deprived of the wide application which for many years we attributed to it," for he wrote:

> In face of the evidence which has now been accumulated, I can no longer regard the . . . theory [of subsidence] as generally applicable. . . . No satisfactory proofs of a general subsidence have been obtained from the region of coral reefs, except from the structure of the reefs themselves, and this is an inference only, which is now disputed. From the nature of the case, indeed, traces of subsidence can hardly be expected.

True, the fact that the depth of certain barrier-reef lagoons had been found greater than 20 or 25 fathoms, the limiting depth for the growth of reef-building corals, was taken to indicate subsidence for those particular reefs, but not for other barrier reefs within which the lagoons were shallower.

Yet it is precisely a general proof of subsidence, at once simple and convincing, that had been independently discovered and published by an earlier and responsible investigator thirty years before, and that was completely overlooked by those who accepted the newer theories; namely, the occurrence of embayments in the central islands of barrier reefs, by which Dana had not merely given new support to, but had provided much-needed confirmation for Darwin's theory; and the most curious thing about the matter is that the eminent geologist, who, after he had abandoned Darwin's theory, championed the still-stand theory in the sentences just quoted, had himself, in an admirable book written nearly twenty years earlier, explicitly recognized the origin of embayments by submergence; for he then said:

> The sea lochs of the west coast [of Scotland] are thus not cut out by the waves, but old glens that have been submerged beneath the sea.

This is just as true for the numerous bays of the antipodal island of New Caledonia with its great barrier reefs as for the sea-lochs of Old Caledonia. In view of all this one must wish that the above-quoted champion of good work in all branches of geology would apply the elementary physiographic principle of shoreline development, not only to the drowned glens of Scotland, but also to the embayments of the reef-encircled Pacific islands where it is so clearly pertinent, and thereupon modify his conclusion that the theory of subsidence is no longer generally applicable in the explanation of coral reefs; for we may surely say of him what he said of an earlier student: The example of Darwin's own candor and overmastering love of truth remains to assure us that no one would have welcomed fresh discoveries [or, as we may interpolate, the resurrection of old discoveries] more heartily than he, even should they lead to the setting aside of his own work.

When the history of natural science is written, it will, I believe, come to be regarded as a curious commentary on the scientific methods of the nineteenth century, that choice among the various hypotheses invented for the explanation of coral reefs was guided so largely by personal habits of thought rather than by logical demonstration; for clearly enough the really successful one among all the proposed hypotheses can be detected only by its ability to survive a crucial test; that is, by its capacity to explain certain essential facts not in mind when it was invented and not explicable by any other hypothesis. A still more curious comment will be pronounced on the coral-reef chapter of scientific history, when it is learned that, as has been shown, a crucial test of the most admirably simple and convincing kind had been, as far as barrier reefs are concerned, discovered and announced a very few years after the publication of Darwin's theory of subsidence, but that it remained unnoticed for years thereafter. It never came to the attention of the author of the subsidence theory himself, perhaps because, as he wrote, "geologists do not read each other's books"; and it seems to have been altogether unknown to the inventors of the later alternative theories, who, had they been better informed, would have at once perceived that their inventions were incompetent.

Dana's Confirmation of Darwin's Theory.—From what has now been said, the nature of Dana's confirmation of Darwin's theory must be clear. The only obscure matter is: why was the clear confirmation so generally overlooked? Dana wrote in his report on the Geology of the United States Exploring Expedition, published in 1849:

> The very features of the land [of barrier-reef islands], the deep indentations, are sufficient evidence of subsidence to one who has studied the character of the Pacific islands.

Farther on in the same volume, under the general heading, "Evidence of Subsidence," and the special heading, "Deep Bay-indentations in Coasts as the Terminations of Valleys," he stated the case more fully as follows:

> In the remarks upon the valleys of the Pacific islands, it has been shown that they were in general formed by the waters of the land, unaided by the sea; that the sea tends only to level off the coast, or give it an even outline. When therefore we find the several valleys continued on beneath the sea, and their enclosing ridges standing out in long narrow points, there is reason to expect that the island has subsided after the formation of the valleys. For such an island as Tahiti could not subside even a few scores of feet without changing the even outline into one of deep coves or bays, the ridges projecting out to sea on every side. . . . The absence of such coves, on the contrary, is evidence that any subsidence which has taken place has been comparatively small in amount.

This explanation has been abundantly confirmed by later investigations, the principles that it involves are to-day everywhere accepted as fundamental in the study of shorelines. The submergence of a mountainous coast must necessarily produce an embayed shoreline, with many out-stretching points of the land separating as many in-reaching arms of the sea. Bays thus produced are often called drowned valleys, in view of their origin. They are beautifully exemplified in many parts of the world far outside of the coral zone, as in the accompanying view of the Bay of Islands in northern New Zealand, Fig. 16. Simple as the explanation of embayed shorelines by submergence is, it was first recognized by Dana in 1839 when he was on a mountain peak in Tahiti; he was indeed the first man in the whole world to perceive that valleys, half drowned by submergence, must form bays; and conversely that bays, which are continued downward from the non-drowned upper part of valleys, demonstrate submergence. But it was not alone that Dana gave this simple explanation of embayed coasts; he demonstrated further that embayments can not be the work of the sea, as seems to have been Darwin's idea, for Dana saw that the sea, unhindered by coral reefs in its attack upon a land margin, tends to simplify an indented coast line by cutting back its promontories, so that the complexity of outline seen in an alternation of lobate promontories and branching bays, interlocking with one another in intricate fashion when initiated by sub-

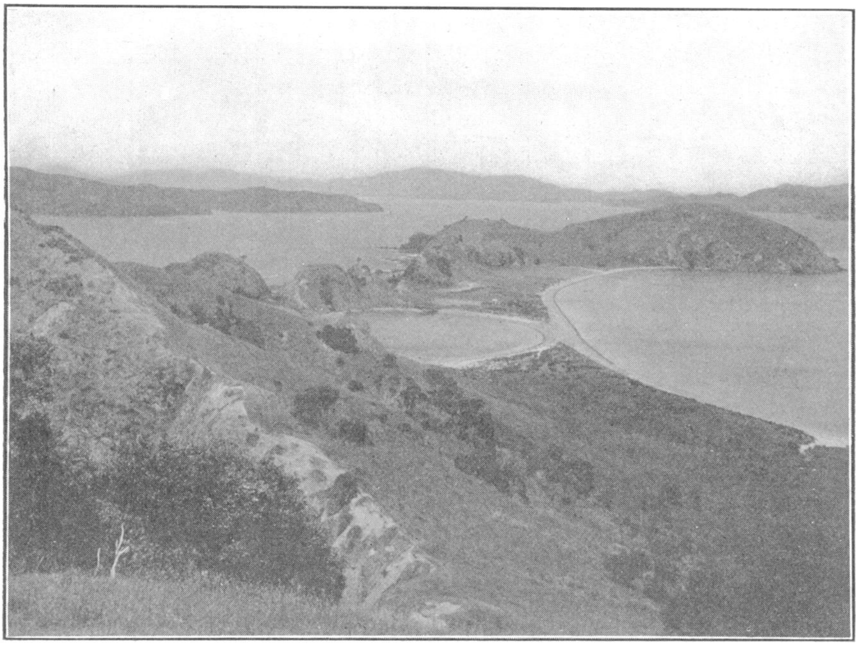

FIG. 16. PART OF THE BAY OF ISLANDS, a half-submerged district in northern New Zealand.

sidence, would be changed to a less irregularity of outline as the land heads were cut back in retreating cliffs, and the bay heads were filled up with advancing deltas; and that there would eventually be developed a marked simplicity of outline when the cliffs were cut farther back than the initial heads of the bays. Dana had good ground for his explanation, for he was convinced that the valleys of the land, be they the short radial valleys such as he saw on the island of Tahiti, or the great complex of valleys such as he observed in the Blue Mountain plateau of Australia, are the product of subaerial erosion which works only above sea-level; it was for this good reason he concluded that a valley which is prolonged in a bay necessarily indicates submergence. This point is evidently important; for if a bay occupy a reentrant between two salient lava flows, as at *K,* Fig. 17, such as occur on the Fiji island of Taviuni, where recent volcanic action has taken place; or if a bay occupy part of a down-faulted trough or bight in a volcanic cone, as at *L* or *M,* such as perhaps occurs in the Fiji island of Moala; or if a bay occupy a large caldera, like that of Totoya, already mentioned, no subsidence would be thereby proved, inasmuch as these peculiar and easily recognizable forms can be produced by volcanic action either at or below or above sea-level: yet if the sides of an embayed bight *Q,* or trough *O,* are ravined, as in Fig. 18, and each ravine descends to a cove

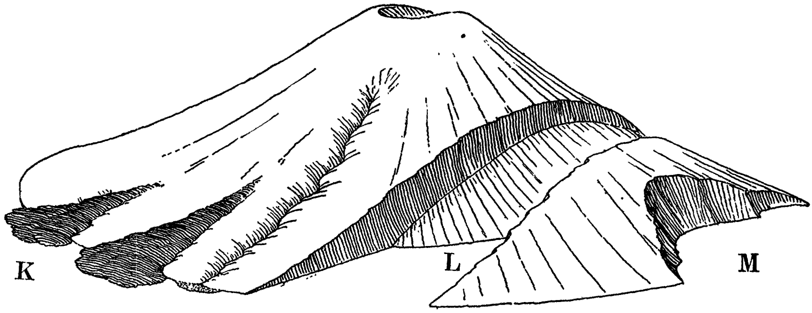

FIG. 17. DIAGRAM OF EMBAYMENTS AS IMAGINED ON A NON-SUBSIDED VOLCANIC ISLAND; *K,* between two advancing lava flows; *L,* in a transverse down-faulted trough; *M,* in a landslide cavity.

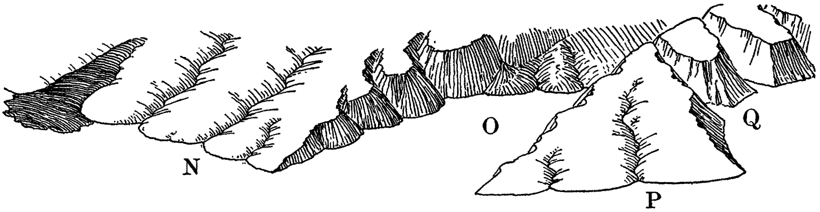

FIG. 18. DIAGRAM OF PART OF THE SAME ISLAND AFTER SLIGHT DISSECTION AND PARTIAL SUBMERGENCE, showing reentrant embayments at valley mouths, *N, P;* and around the ravine sides of a down-faulted trough, *O,* and of a landslide cavity *Q.*

in the shoreline of embayment, the side coves prove submergence after the down-faulting and erosion, even if the embayment of the down-faulted space does not; and such is the case in Moala: likewise, small embayments in a dissected caldera wall prove submergence, and such is the case in the ring-island of Totoya.

The Embayments of Barrier-Reef Islands.—But to return to our coral reefs. If it be true on general principles that the embayments of a dissected central island demonstrate that submergence took place while the encircling barrier reef grew upward, is it also true that the central islands within barrier reefs are so generally embayed as thereby to establish, for barrier reefs at least, the truth of the subsidence theory? Yes, abundantly so; and not only are they elaborately embayed, but their embayment has long been represented on charts and stated in descriptions. Ninety years ago the same two missionaries who first suggested that coral reefs might be formed on wave-cut platforms, described the island of Tahaa, Fig. 19, in the Society group as distinguished "by the number, breadth and commodiousness of its harbors, with which the

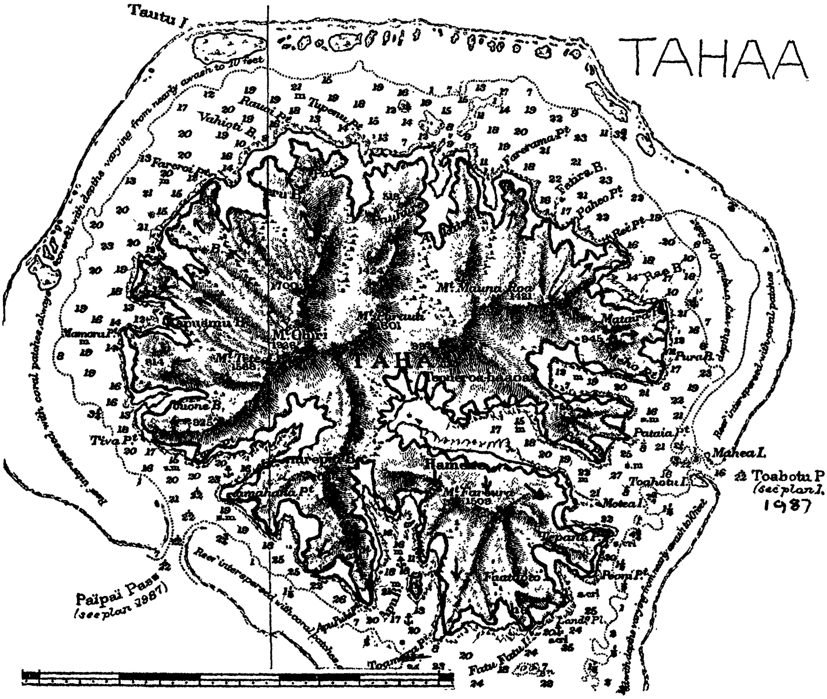

FIG. 19. BRITISH ADMIRALTY CHART OF TAHAA, SOCIETY ISLANDS. The outermost belt, with curved lines of fine print, is the barrier-reef flat; the lagoon is dotted with soundings in fathoms; a narrow fringing reef follows most of the present shore line; delta plains are blank, between the present shore line and the more sinuous original shore line (added in a heavy line) caused by submergence of the maturely dissected volcanic cone.

whole coast is indented, some running quite into the heart of the country"; thus its outline is made so irregular that the natives compare it to a cuttle-fish, "the projecting headlands and intrusive creeks resembling the many tails or tentaculæ" of that animal. I went around the lagoon of Tahaa in a small motor boat, passing all its spur-end points and entering some of its larger bays, taking time to note the form of the spur-ends where they are cut off in low cliffs, and to sketch the inner border of the bay-head delta plains, in order to reconstruct the intricate salients and embayments that its shores would possess if the spurs had not been a little cut back, and if the deltas had not been built forward. The result is shown by the innermost and strongest black line of Fig. 19—the outermost line is the barrier reef—and it appears to me to be a result of a very striking nature. The small arrows on the spurs represent the dip of lava flows and ash-beds: their radial arrangements shows that the island represents a single volcanic cone, elaborately dissected and partly submerged. Evidently enough the bays would be much longer and more branching than now, if the deltas were removed; and as evidently the spur-ends would not be much longer than now if their original points were restored; but most evident of all, the outline thus reconstructed can be explained in no other way than by the submergence of an elaborately dissected volcano.

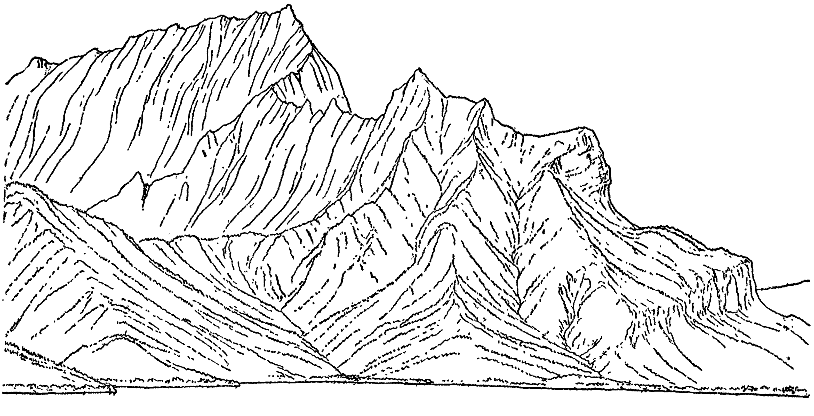

Fig. 20. Sketch of part of the Deeply Dissected Volcanic Mass of Raiatea, Society Islands. The embayment of the shore line, diminished by deltas, is not clearly shown because of foreshortening. Fig. 5 is a bay in the same island.

Let it not be supposed that Tahaa is of exceptional pattern. The neighboring islands of Raiatea, Fig. 20, was instanced by Darwin seventy years ago as possessing "those deep arms of the sea . . . which penetrate nearly to the heart of some encircled islands." I gave two days to the leisurely circuit of its lagoon. How wonderfully its original shape is transformed! How deep are the valleys between the sharp-crested ridges! How gently the spurs slope down, hardly nipped at their ends, into the enclosed lagoon! Again, the Fiji islands make one of the groups in which Dana found many embayed islands to support Darwin's theory, yet that group has been said by some observers to occupy an area not of subsidence but of elevation, because elevated reefs occur on some of the islands. Such a statement is geologically altogether inconclusive; for the absence of elevated reefs on many members of the Fiji group shows that they have not suffered elevation. I saw eighteen of the Fiji islands on my voyage, and sixteen of these had embayed shorelines; the other two showed elevated reefs, as yet little dissected and hence lately elevated. A willing witness to subsidence in Fiji is the little island of Ono, Fig. 21, of mountainous form and irregular outline. A more striking example is the larger island of Ka-ndá-vu, Fig. 22, next southwest of Ono; there the mountains are higher and the embayments are more pronounced; they indicate a recent subsidence of at least 600 or or 800 feet. When this is taken in connection with the elevated reefs of Fiji, some of which have been recently uplifted from 600 to 1,000 feet, a gentle warping of the ocean bottom is indicated; but that is not a surprising matter.

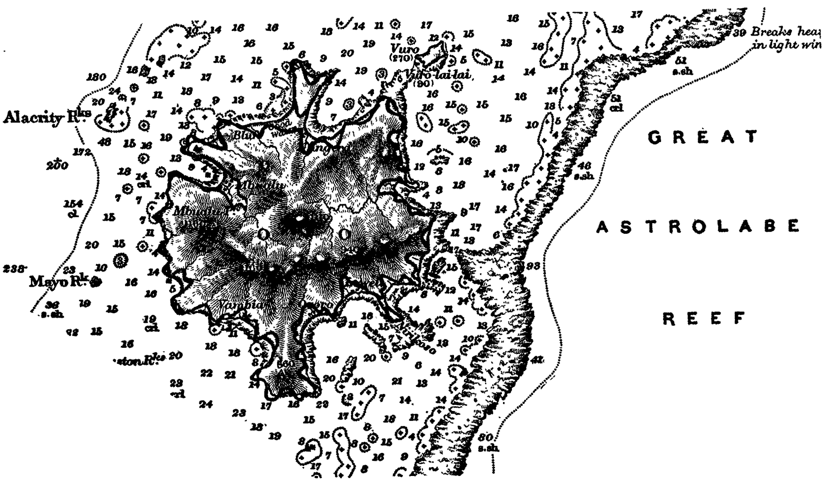

FIG. 21. BRITISH ADMIRALTY CHART OF THE EMBAYED ISLAND OF ONO IN THE GREAT ASTROLABE REEF, FIJI. The shore line of submergence is added in a heavy line. The larger island of Kandavu, Fig. 23, lies next southwest.

The Surprising Case of Ka-ndá-vu.—Indeed, the only surprising thing in association with the beautiful island of Ka-ndá-vu is, not the embayments of its shoreline, not the strong subsidence to which the embayments testify, but the statement regarding the island made by the chief advocate of the still-stand theory of outgrowing reefs: he wrote, several years after his visit to this island:

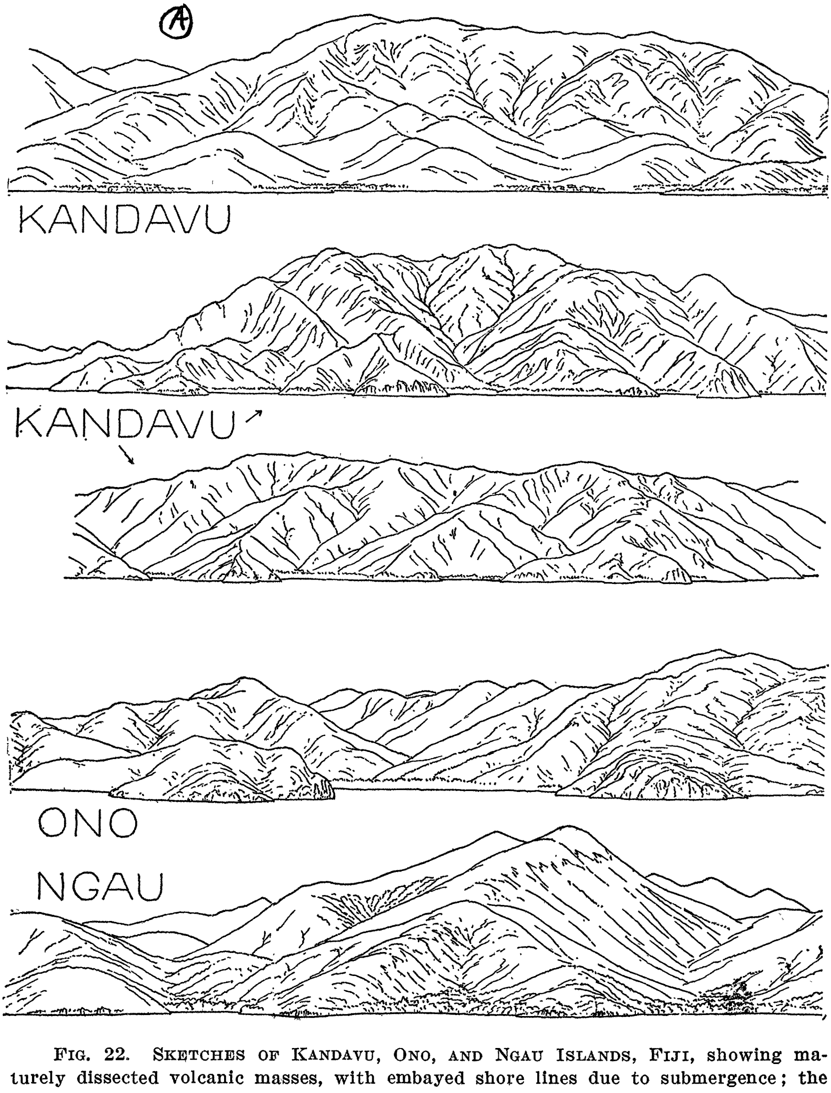

Fig. 22. Sketches of Kandavu, Ono, and Ngau Islands, Fiji, showing maturely dissected volcanic masses, with embayed shore lines due to submergence; the bay heads are occupied by deltas; some of the land heads are cliffed more than usual.

> It was here that, not being able to apply Mr. Darwin's theory in explanation of the phenomena of the Kandavu reefs, I commenced to doubt it altogether. . . . The more observations accumulate the more does it seem to me probable that there never was a barrier reef or atoll formed after the manner required by Mr. Darwin's theory.

That is truly astonishing, indeed astounding! On reading it in presence of a detailed map of Ka-ndá-vu, Fig. 23, or still better in presence of the island itself, it will be understood more fully than before why the still-stand theory of coral reefs must, in so far as barrier reefs

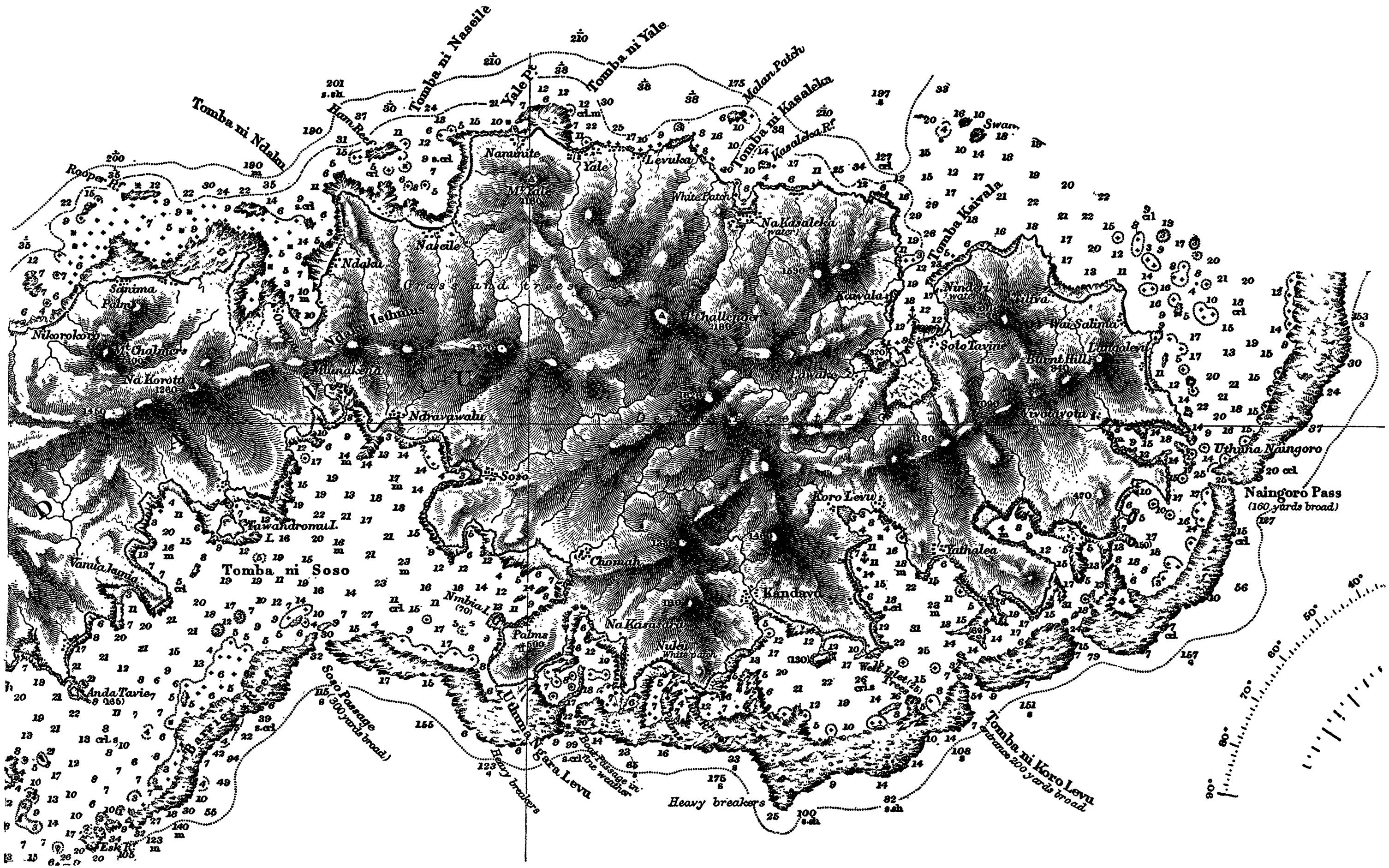

FIG. 23. BRITISH ADMIRALTY CHART OF THE EASTERN HALF OF KANDAVU, FIJI, showing its elaborate embayments. A fringing reef follows the shore line; the barrier reef is broad and continuous on the southeastern or windward side, and discontinuous or wanting on the northwestern side. Scale, about 1 : 87,000, Ono, Fig. 21, lies next northeast.

are concerned, be regarded as a scientific blunder and its publication a bar to progress; for if one island had to be selected from all the islands of the Pacific as decisively favoring Darwin's theory, that island might well be Ka-ndá-vu. Yet hardly less unwarranted than the above quotation is the assertion by the same author that the still-stand hypothesis is in harmony with Dana's views of "the great antiquity and permanence of the great ocean basins"; for if there was any one man who believed that the bed of the ocean basins has not always stood still, but has sometimes subsided, that man was Dana.

In view of all this, it is inevitable that any hypothesis which postulates a fixed relation between the island foundations of coral reefs and the level of the surrounding ocean must be rejected. It may seem overbold thus on the ground of physiographic evidence summarily to set aside certain hypotheses that have been accepted by able investigators; and so indeed it would be had those investigators recognized the occurrence of embayed central islands, and had thereupon said: "Truly these embayments appear at first sight to be drowned valleys, but further study shows them to be of quite different origin, independent of subsidence"; but unfortunately they said nothing of the kind; they took no account of embayments at all. It is therefore well warranted to say, in view of the widespread occurrence of embayed central islands, that the postulate of a fixed relation of island mass to ocean surface is inadmissible. Theories of coral reefs and theories of ocean basins must include the possibility of a mobile ocean floor that carries oceanic islands up or down as it rises or subsides, or of a variable ocean surface that, as it subsides or rises, allows the emergence or submergence of still-standing islands.

The Evidence of Elevated Reefs.—We have thus far considered chiefly barrier reefs at sea-level. Let us now ask what testimony elevated reefs offer, for elevated reefs were specified on an earlier page as competent and communicative witnesses, whose testimony must be heard. But in order to appreciate the value of this testimony, let it be clearly understood that the still-stand theory requires elevated reefs to rest conformably on non-eroded volcanic slopes, because according to this theory, reefs must lie on a slope that has never subsided from a higher stand in which it might have suffered erosion; while the subsidence theory as definitely requires elevated reefs to rest unconformably on a slope that was eroded before it subsided.

An elevated reef, standing 20 or 25 feet above sea-level, has long been known to form a plain of variable width on the border of the Hawaiian island of Oahu, especially along its southern and western sides. The conditions of its origin have been much discussed. That it was formed during or after a time of submergence is clearly proved by the following considerations: Oahu consists of the remains of two great volcanoes, an older and more dissected cone forming the smaller, western part of the island, and a younger and less dissected cone forming the the larger eastern part. Some of the valleys in the older western mass, Fig. 24, are one or two miles in width at the shoreline, and are enclosed by high, narrow, steep-sided spurs, on the flanks of which gently inclined lava beds outcrop in great number. The original floor of the valleys is not now visible, because each valley is occupied, in its shoreward part at least, by the lagoon-limestone plain of the elevated reef: the floor of volcanic rock must be, as well as one can judge by the slope of the valley-side spurs, hundreds of feet below the limestone plain; and this inference is confirmed by the depth of several artesian wells in limestone or non-volcanic beds. Hence the island must have stood hundreds of feet higher than now when the valleys were eroded, and must afterwards have subsided hundreds of feet in order to allow the lagoon limestones associated with the elevated reef to be deposited in the valleys. Since then, a moderate elevation with resulting erosion has taken place; and afterwards a still more moderate depression, for on the south side of the island the branching bays of Pearl harbor are nothing more or less than valleys eroded in the elevated reef plain and then drowned. The present sea-level reef of Oahu was formed in association with the depression that formed Pearl harbor.

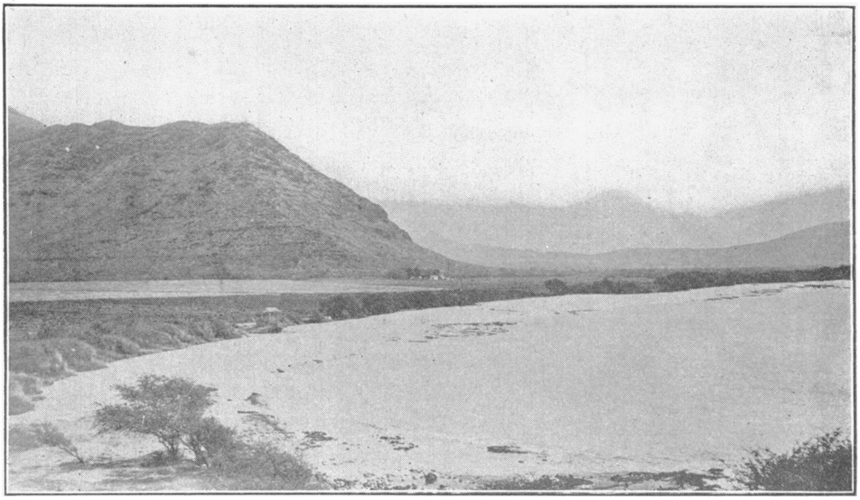

FIG. 24. A LAVA-BED SPUR BETWEEN TWO BROAD VALLEYS OF THE WEST COAST OF OAHU, Hawaii. The valley floors are entered by the limestones of the elevated reef which forms the coast plain.

Elevated reefs are found on many islands in the larger archipelagoes of the western Pacific. In the Philippines the island of Cebú is terraced with reef limestones which rest unconformably on an eroded foundation of older rocks; and in such a case, as well as in Hawaii, the foundation mass must formerly have stood at least as high as now in order to suffer erosion; it must then have been submerged to the level of the highest limestone terrace at least; and it must finally have been uplifted to its present altitude. It is of course possible that the terracing reefs may have been formed during pauses in a slow emergence following a rapid submergence; but it is also possible that they were formed during pauses in a slow submergence followed by a rapid emergence; and it is again possible that some terraces were formed during pauses in submergence, and others during pauses in emergence. Nothing less than close study of the terracing structures will suffice to determine which of these possibilities corresponds to the actual occurrences of past time; but while we are waiting for such study, it is fair to quote this case as demanding submergence as a factor in the formation of the reefs in question, and as thereby warranting the postulate of submergence in other cases. Many other examples of unconformable elevated reefs might be cited: they all testify as unequivocally to the submergence of the eroded reef foundation before the reefs were formed or while they were forming, as to the emergence of the compound mass after the reefs were formed.

Which Theory is Best?—In view of the various sea-level and elevated reefs in situations so significant as those now mentioned, can any one who carefully deduces the consequences of the three hypotheses thus far presented, hesitate for a moment in making his choice among them? In the case of sea-level barrier reefs, where are the confluent deltas, projecting outside of a non-embayed initial shoreline, as demanded by the hypothesis of outgrowing sea-level reefs on still-standing islands? Where are the cliffs around a non-embayed shoreline, as demanded by the theory of veneering reefs on wave-cut platforms? And where are not the re-entrant embayments, with small deltas at their heads, as demanded by the hypothesis of upgrowing barrier reefs on subsiding foundations! In the case of elevated reefs, where are the unworn volcanic slopes beneath the steeply inclined talus of coral waste, as required by the theory of outgrowing reefs; or the truncated platforms beneath a coral growth of small thickness, as required by the theory of veneering reefs? And where are not the unconformable contacts of reef limestones upon an eroded foundation slope, as required by the subsidence theory!

The Origin of Atolls.—The confirmation provided for Darwin's theory by Dana's principle of shoreline development is as admirable and abundant for sea-level barrier reefs as is that provided by the unconformable contact of reef-mass and foundation for elevated reefs: but let it be explicitly noted that neither of these confirmations applies directly to sea-level atolls. Those inscrutable islands stand alone in the sea, without witnesses to reveal their origin. They have been described as monuments over drowned volcanoes; they are monuments truly enough, and it has lately been shown that the Bermuda reefs have a volcanic mass beneath them; but no direct proof has been found that any sea-level atoll in the Pacific is built upon a volcanic foundation, much less that the foundation has subsided. The deep boring on the atoll of Funafuti in the Ellice group has led different students to different conclusions, though it seems to me that the evidence for subsidence is strong: unhappily the boring reached no volcanic rock. Nevertheless, it is probable that the atolls of the Pacific have subsiding volcanic foundations for the following reasons. Atolls sometimes occur in association with barrier reefs, as in the Fiji, New Hebrides and Society groups; and in such cases the subsidence of the volcanic islands proved for the barrier reefs may be very reasonably extended to the neighboring atolls. Sea-level atolls are in all cases exactly like barrier reefs, but for the absence of a central island; the process which has produced a barrier reef on a subsiding volcano must, if continued, change it into an atoll; and it would truly be singular if this process, so far advanced in some barrier reefs that their central islands occupy a very small fraction of their lagoon, had never continued a little farther; Maré, Fig. 25, the southeasternmost of the Loyalty islands, is a recently uplifted atoll, about twenty miles in diameter, and over 200 feet above sea-level; it has a low knob of eroded volcanic rock near the center of the limestone plain that represents the former lagoon, but the summit of the knob is lower than the reef-rim that encloses the plain, and hence the volcanic summit was below sea-level before uplift occurred. No uplifted atolls have been found to possess the particular structures characteristic of atoll formation by other processes than upgrowth during subsidence. On the other hand, the extensive oceanic subsidence demanded by the occurrence of atoll groups has been objected to as inconsistent with what is known of the origin of ocean basins; but so little is known of their origin that this objection has little force; the theory of ocean basins must accommodate itself to the subsidence that is demonstrated for barrier reefs and made highly probable for atolls.

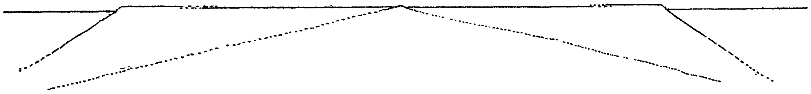

FIG. 25. CROSS SECTION OF THE ELEVATED ATOLL OF MARÉ, LOYALTY ISLANDS, showing the small knob of volcanic rock that rises in its lagoon plain to a less height than its reef rim.

Atolls Formed by Up- and Out-growth.—Let us now turn aside from the theory of subsidence and consider briefly another theory for the formation of atolls, proposed by the oceanographer who advocated the still-stand theory of barrier reefs. Let *VVV*, Fig. 26, be a submarine mountain, presumably a volcano, the summit of which lies below the limiting depth of 20 or 25 fathoms, at which reef-building corals can grow. The frail calcareous shells of innumerable small pelagic animals, floating in the shallower waters, fall to the ocean bottom when the animals die, like "an organic rain"; and, in so far as they fall on the mountain, they aid the organisms living there to build it up, *QQ;* and thus eventually a submarine bank is formed near enough to the surface for corals, *NN,* to be established upon it. Then the corals grow outward on their own talus and form an enlarged atoll reef, *RR,* while the older part of the reef is dissolved out to form the lagoon. Such is the hypothesis for the production of atolls by up- and out-growth without subsidence. It is easily conceivable, but no one has yet shown that it represents any actual occurrence. Soundings have truly enough discovered organic deposits on submarine summits, but it does not seem probable that the fine calcareous deposits of the "organic rain" could remain on a summit when it reached depths less than 40 or 30 fathoms; the heavy waves of the ocean would sweep the deposits off into deeper water, and upbuilding would have to be continued by heavier forms of local growth. But it is not known that submarine summits stand still and suffer a capping of organic deposits to grow upwards nearly to the sea surface. So far as islands which rise above sea-level are concerned, their heads are as uneasy as if they wore a crown; emerged summits repeatedly suffer uplift or depression as well as still-stand pauses: it is therefore probable that submarine summits are similarly uplifted or depressed, for uplift and depression of super- or submarine volcanic masses do not result from changes within the masses themselves, but from movements in the suboceanic earth crust on which they stand. If the submarine summits are depressed, they could hardly be at the same time built up to the surface by the slow process of "organic rain"; if elevated, it is certainly singular that they all stop rising in the regions of true atolls before they emerge. Hence this theory is encompassed with improbabilities.

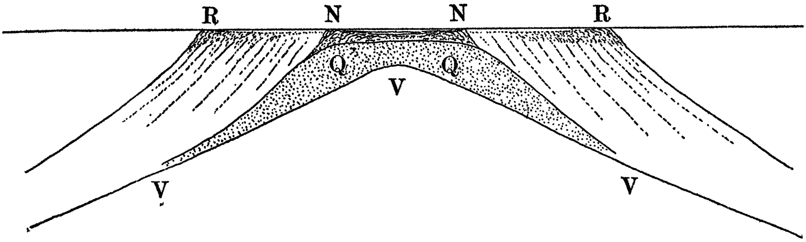

FIG. 26. CROSS SECTION TO ILLUSTRATE THE THEORY OF UP- AND OUT-GROWING REEFS: a submarine volcanic summit *V*, is built up with pelagic deposits, *Q*, and crowned with a reef, *N*, which has been enlarged by out-growth, *R*.

Furthermore, no elevated atoll has been described as showing the structures demanded by this theory; hence the theory stands merely as a possibility without direct support. But an island in the Solomon group has been figured as possessing a volcanic core, *V,* Fig. 27, partly covered by pelagic deposits, *LL,* other than coral, and these in turn are surrounded by an uplifted coral-reef terrace, *RR,* not so high as the pelagic deposits: and this composite structure has been taken as confirming the up- and out-growth hypothesis just stated. The confirmation is not convincing for several reasons. First, the volcanic summit, *V,* has a greater altitude than the pelagic deposits, *L,* and this would seem to show that the summit had been built up above sea-level before the "organic rain" fell on its flanks. Second, the pelagic deposits, *L,* have a greater altitude than the coral reef, *R,* and this shows that uplift of the cloaked volcano preceded as well as followed reef formation. Third, the threefold structure is vertically exaggerated in Fig. 27; it might be better represented by *VLR,* Fig. 28. Fourth, the contacts of the pelagic deposits with the volcanic cone, and of the reef limestones with the pelagic deposits remain undescribed: perhaps, instead of representing an unbroken succession of submarine deposits, they may be separated by surfaces of erosion, and thus represent discontinuous deposits, as *UJS;* that is, the volcano may have stood above sea-level and suffered erosion for a time, before rapid subsidence drowned it for the receipt of the uncomformable pelagic cover; uplift and erosion of the composite mass may then have taken place before renewed subsidence permitted the formation of the reef; not till then may have come the present uplift of the threefold mass. Changes of this kind may seem cumbrous. If so, let me commend the attentive study of the following example from the new Hebrides.

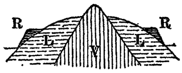

FIG. 27. REPRODUCTION OF A CROSS SECTION OF ONE OF THE SOLOMON ISLANDS, much exaggerated vertically.

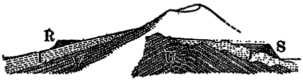

FIG. 28. THE SAME, REDRAWN WITH LESS VERTICAL EXAGGERATION, showing on the left a volcanic slope, *V,* conformably overlaid with pelagic deposits, *L,* and these conformably built upon by a reef, *R;* the threefold mass having been twice elevated. On the right, the three structures, *U, J, S,* are drawn with unconformable contacts, indicating two depressions and two uplifts.

Uplifted Reefs in the New Hebrides.—On the northwest side of the island of Efate in the New Hebrides a series of well-bedded, nearly horizontal tuffs, *NN*, Fig. 29, described as containing *Globigerina* and other pelagic foraminifera, is deeply eroded in valley-side slopes of over 800 feet, which descend to the drowned-valley embayment of Havannah harbor; and the slopes are terraced by a number of elevated fringing reefs, *TTT*, which contain abundant and well-preserved fossil corals, and which lie unconformably on the eroded slope of the tuff beds. If this is interpreted in accordance with well-established geological principles, we must conclude that the island stood several hundred feet lower than now when the foraminiferal tuffs were deposited: that it was then raised higher than now for the erosion of the drowned valley of Havannah harbor; that it then subsided low enough for corals to form fringing reefs up to the very top of the eroded slope; and that it was finally raised at least to its present altitude, leaving the valley bottom drowned. Whether the fringing-reef terraces were formed during the last uplift or during the preceding subsidence is not easy to determine; their formation during uplift has been announced by a young Australian observer, but he did not recognize that the truncation of the tuffs demanded previous elevation, erosion and depression. In company with Mr. E. C. Andrews of Sydney, New South Wales, I reviewed the section with the earlier observer's report in hand; and the formation of the reefs during intermittent subsidence followed by rapid uplift, rather than during intermittent uplift preceded by rapid subsidence, seemed an explanation well worth considering. Whether the tuffs of Efate lie on an eroded or a non-eroded volcanic foundation, *WW*, I can not say; but in Viti Levu, the largest island of the Fiji group, similar marine tuffs seemed to lie, at the only point of near-contact that I reached, unconformably on an eroded volcanic slope; if the same relation occurred on Efate, a strong submergence must have taken place after the initial volcano was built up and eroded, and before the tuffs were laid down on its eroded flanks. The absence of details of this kind from the

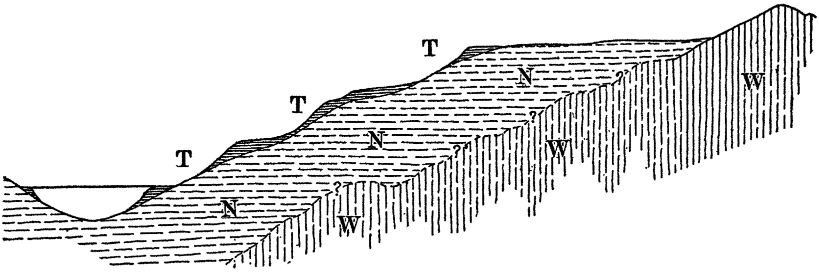

FIG. 29. CROSS SECTION TO ILLUSTRATE THE UNCONFORMABLE CONTACT OF THE ELEVATED FRINGING REEFS OF EFATE, in the New Hebrides group, on an eroded mass of horizontal marine strata, *NN*; the nature of the contact of the marine strata on their volcanic foundation, *WW*, is not known.

description of the island in the Solomon group (Fig. 27) makes it for the present an incompetent witness. The upshot of all this is, that the up- and out-growth hypothesis, which explains atolls as the crowns of pelagic deposits built up on submarine foundations, is as yet without support by well-observed facts; and hence that Darwin's theory of subsidence provides a simpler and better supported explanation of atolls than any theory yet invented.

Objections to the Theory of Subsidence.—Are we then to understand that no objections can be raised against the theory of subsidence? Hardly that, for many objections deserving consideration have been urged. First is the objection that an extravagantly large volume of limestone is needed to build atolls on the subsidence plan. This is perfectly true, but it is also true that the outgrowth plan is hardly less extravagant. Extravagance seems sometimes to be the order of nature, as in building up voluminous volcanic cones by eruption through the earth's crust beneath the ocean; some of the cones, if measured from the ocean bottom, are of staggeringly large dimensions. But the best answer to this objection is found in two of the Loyalty islands, next northeast of New Caledonia; they are uplifted atolls 20 or 30 miles in diameter and now standing 200 or 300 feet above sea-level, without a sign of any rock but limestone around their rim, though one of them (Maré) has, as above mentioned, a small knob of volcanic rock in the center of its uplifted lagoon-plain; if the volcanic mass of which the knob is the summit be given a slope such as is commonly observed in volcanic islands of the Fiji group, the thickness of the limestones at the margin of the island must be at least 5,000 or 6,000 feet. As far as this goes, it indicates that heavy limestone masses really do occur beneath the crown of an atoll reef.

A second objection to the theory of subsidence is based on the absence of heavy coral-reef limestones from ancient geological formations. To this it may be answered that, while parts of continents have in the past presumably been transformed by depression into deep ocean floors, deep ocean floors do not seem to have been transformed by elevation into continents; or if they have been, the lofty overtopping atolls then uplifted must, as a rule, have been worn away, just as all lofty mountains and volcanoes of Paleozoic and Mesozoic times have been worn away. The roots of ancient mountains and volcanoes are found beneath less ancient geological formations, but not the summits. Similarly, it is only the base of ancient atolls that would commonly be preserved under less ancient geological formations, and not the tops. Another answer to this objection is that the heavy dolomites of the Tyrol do, by way of exception, represent ancient coral reefs, and thus show that ancient reefs are occasionally preserved.

A third objection to the theory of subsidence is, as above noted, the necessity of a great depression of the Pacific ocean floor in recent geological time over the immense area occupied by groups of barrier reefs and atolls. So great a depression is held by some to stand in contradiction to what is known of the dynamics of ocean basins; but in answer it may be urged that the evidence of strong ocean-bottom subsidence over large areas, as given by atolls, must be added to the little else that is known about the ocean floors before safe inferences can be drawn as to the amount of deformation which their basins have suffered. It may be briefly noted that the inferred contemporaneous lowering of ocean water and the consequent laying bare of all continental coasts, as a result of a great deepening of the Pacific atoll areas, is not necessary; for it may be assumed with much probability that adjacent parts of the Pacific floor suffered a roughly compensating elevation, as Darwin suggested, when the atoll areas subsided, and hence that contemporaneous changes of ocean level were relatively small.

A fourth objection to the theory of subsidence, urged by an eminent geologist, must be regarded as the most singular of all objections. It is as follows: "Upheaval has taken place in areas where barrier reefs and atolls are in vigourous growth. Such an association of upheaval with an assumed general subsidence requires, on the subsidence theory, a cumbrous and entirely hypothetical series of upward and downward movements," and hence is improbable and unacceptable. This pronouncement is, in view of its source, one of the most extraordinary that I have encountered in coral-reef literature. It tempts me to follow for geologists the example of the late William James, who divided philosophers into two categories, the tender-minded and the tough-minded. Let us divide geologists into the same two classes, and among the tender-minded place those who hesitate to accept a theory of coral reefs that involves repeated uplifts and depressions of the earth's crust because such terrestrial uneasiness is mentally distressing; and among the tough-minded, those who are perfectly ready to follow good evidence wherever it leads, even to the cumbrous series of upward and downward movements shown by elevated reefs in Fiji and by Efate in the New Hebrides. It is consoling to remember that James avowed himself to be one of the tough-minded pragmatical lot.

(*To be continued*)